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# Life cycle assessment of an offshore grid interconnecting wind farms and customers across the North Sea

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**Abstract**
*Purpose* This study aims to contribute to an improved understanding of the environmental implications of offshore power grid and wind power development pathways. To achieve this aim, we present two assessments. First, we investigate the impacts of a North Sea power grid enabling enhanced trade and integration of offshore wind power. Second, we assess the benefit of the North Sea grid and wind power through a comparison of scenarios for power generation in affected countries.
*Methods* The grid scenario explored in the first assessment is the most ambitious scenario of the Windspeed project and is the result of cost minimization analysis using a transmission-expansion-planning model. We develop a hybrid life cycle inventory for array cables; high voltage, direct current (HVDC) links; and substations. The functional unit is 1 kWh of electricity transmitted. The second assessment compares two different energy scenarios of Windspeed for the North Sea and surrounding countries. Here, we utilize a life cycle inventory for offshore grid components together with an inventory for a catalog of power generation technologies from Ecoinvent and couple these inventories with grid configurations and electricity mixes determined by the optimization procedure in Windspeed.
*Results and discussion* Developing, operating, and dismantling the grid cause emissions of 2.5 g $CO_2$-Eq per kWh electricity transmission or 36 Mt $CO_2$-Eq in total. HVDC cables are the major cause of environmental damage, causing, for example, half of total climate change effects. The next most important contributors are substations and array cabling used in offshore wind parks. Toxicity and eutrophication effects stem largely from leakages from disposed copper and iron mine tailings and overburden. Results from the comparison of two scenarios demonstrate a substantial environmental benefit from the North Sea grid extension and the associated wind power development compared with an alternative generation of electricity from fossil fuels. Offshore grid and wind power, however, entail an increased use of metals and, hence, a higher metal depletion indicator.
*Conclusions* We present the first life cycle assessment of a large offshore power grid, using the results of an energy planning model as input. HVDC links are the major cause of environmental damage. There are differences across impact categories with respect to which components or types of activities that are responsible for damage. The North Sea grid and wind power are environmentally beneficial by an array of criteria if displacing fossil fuels, but cause substantial metal use.

**Keywords** Carbon footprint · Grid integration · Hybrid LCA · HVDC transmission · Variable renewable energy · Windspeed

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## 1 Introduction

There is a growing interest in electricity grid development in the North Sea (EC 2010a, b; EWEA 2009; Veum et al. 2011). Extending the North Sea power transmission network could have multiple benefits: connect offshore wind farms (electricity producers) or oil or gas platforms (electricity consumers) to transmission systems on land, raise the overall efficiency of electricity supply through enhanced trade, and aid power grid

balancing in systems with high shares of intermittent supply. Subsea power transmission in the Northern Seas is identified as one of four "priority corridors for the transport of electricity" in EU energy and climate policy (Carvalho 2012). Furthermore, renewable energy action plans of EU member states project cumulative deployment of 44 GW offshore wind generation capacity in 2020, up from 0.7 GW in 2005 (Beurskens et al. 2011). These policy plans and priorities are suggestive of a substantial expansion of the North Sea power transmission in the next decade or two—and part of a general expectation that major expansions in electricity transmission and distribution (T&D) are needed to develop reliable and sustainable energy systems for the future (Riahi et al. 2012).

The main motivation for this study is the need to establish good knowledge on the environmental implications of offshore electricity systems. Such systems may play a positive role in phasing out fossil fuels—a generally desired outcome and policy target—but will also in themselves cause harmful emissions and use of nonrenewable resources. Another motivation is the overlap between understanding the impacts of power grids and renewable power generation: Renewable energy resources tend to be located far from consumption centers and thus require more extensive grid connections than fossil power plants. Also, their often intermittent nature leads to generally increased transmission capacity requirements (IEA 2012). Hence, as has been noted before (Arvesen et al. 2011; Jorge et al. 2012a), evaluations of renewable energy ideally should consider impacts due to T&D in order to reflect real-world effects.

As of today, there are only a limited number of environmental life cycle assessments (LCAs) of electricity T&D in the peer-reviewed literature and none, as far as we are aware of, with a main offshore focus. Jorge and colleagues compile and analyze life cycle inventories for electrical grid components (Jorge et al. 2012a, b) and scale up inventories to study the Norwegian transmission network (Jorge and Hertwich 2013). Harrison et al. (2010) study the transmission system in Britain, and Bumby et al. (2010) study the power distribution in California. Jones and McManus (2010) present an assessment of underground and overhead lines used in distribution networks. In addition to dedicated LCAs of T&D, main electrical equipment needed to transfer electricity generated by offshore wind turbines to shore is part of the systems studied in LCAs of offshore wind power (e.g., Wagner et al. 2011; Arvesen et al. 2013). In such studies, electrical connections comprise array cables, an offshore substation, and export cables running from the substation to an existing grid. Alternating current (AC) connections are assumed, and usually, nearshore wind farms are studied (Arvesen and Hertwich 2012).

This study aims to contribute to an improved understanding of the environmental burdens and benefits of ambitious power grid and offshore wind power development pathways for the North Sea. In order to achieve this aim, we present two assessments. First, in the detailed grid assessment, we use the method of a hybrid LCA to examine the environmental impacts associated with building and operating an extensive North Sea power grid, the Grand Design v05 grid defined in the Windspeed project (Windspeed 2014). Second, in a comparative assessment of scenarios, we utilize life cycle inventories for a catalog of power generation technologies so as to assess the environmental burdens and benefits of two energy scenarios for the North Sea and surrounding countries. The Grand Design v05 (GDv05) and In the Deep 20 % (ITD20) scenarios of Windspeed are obtained from solutions of a mixed-integer linear program model, whose objective function seeks to minimize the total costs of satisfying future electricity demand in the North-Sea-neighboring countries with generation and offshore transmission (Huertas-Hernando et al. 2011). The scenarios are described in more detail in section 2.1.

## 2 Case description

### 2.1 Grid scenarios

The offshore wind and grid scenarios examined in this study are obtained from the project Windspeed (SPatial Deployment of offshore WIND Energy in Europe) (Windspeed 2014). Windspeed developed a roadmap that defines realistic targets and a development pathway from 2020 up to 2030 for offshore wind energy in the Central and Southern North Sea (Belgium, Denmark, Germany, the Netherlands, Norway, and Great Britain) (Veum et al. 2011). The work consisted of four phases. In phase one, different uses of marine areas were mapped and characterized. Phase two assessed likely offshore wind energy deployment, taking into consideration the costs and competing uses of marine space. Phase three developed offshore wind and grid scenarios, involving the use of a transmission-expansion-planning tool to identify optimal grid layouts. The last phase put together all information to create a final roadmap.

The grid scenarios aimed to recommend grid development to support offshore wind deployment by considering technical solutions, grid topologies, and infrastructure and operational costs (Huertas-Hernando et al. 2011). The impacts and benefits of the proposed grid configurations for power system and market operation were investigated in detail. A preliminary assessment of $CO_2$ emissions was performed in Huertas-Hernando et al. (2011), but a more comprehensive analysis of environmental impacts and benefits is desired. This is the focus of the present paper.

The specific scenarios analyzed in this work are referred to as GDv05 and ITD20. Both scenarios assume fast technological development and imply a large-scale deployment of offshore wind power, of which a significant share comes from

areas far from shore. The scenarios differ in that GDv05 assumes a higher level of transnational coordination for the development of an offshore grid. GDv05 exemplifies a development where the realization of a highly interconnected transmission network in the North Sea opens doors for enhanced power trade and offshore wind power deployment. ITD20 also involves a large-scale development of a North Sea grid, but the more radial grid layout offers less opportunity for interregional trade and offshore wind electricity. Further, GDv05 is produced under more lenient assumptions about the operating modes of thermal power stations: While GDv05 assumes no minimum production rate bound, ITD20 does not permit production rates lower than 20 % of nominal capacity. Finally, complete phase out of nuclear power is assumed in GDv05 but not in ITD20. As a whole, GDv05 assumptions give more favorable conditions for phasing out carbon-emitting generation sources by large-scale deployment of offshore wind energy. GDv05 is the most pro-offshore wind scenario and the scenario with the most interconnected North Sea transmission network considered in Huertas-Hernando et al. (2011).

The offshore grid maps in Fig. 1 depict wind farm clusters and the transmission network in the North Sea in the year 2030 for GDv05 and ITD20 scenarios individually. Table 1 displays the annual production of electricity in 2030 for the same respective scenarios for four regions, as determined by the optimization procedure used in Windspeed.[1] Note the lower fossil-fuel-based electricity production in GDv05 (126 TWh/year less than for ITD20 in total) and the increase in offshore wind electricity in GDv05 (164 TWh/year more than for ITD20). Figures for renewables other than offshore wind are very similar for the two scenarios.

The GDv05 scenario shows an offshore wind power capacity of 135 GW in 2030, of which 88 GW is connected to the offshore grid depicted in Fig. 1. The corresponding numbers for ITD20 are 93 and 53 GW (Huertas-Hernando et al. 2011). By comparison, the European Wind Energy Association gives a target of 150 GW in 2030 for the whole of the EU, chiefly based on a survey of planned projects (Azau 2011). An accompanying document to the European Commission's Energy 2020 strategy mentions in excess of 140 GW of offshore wind energy plans among member states but gives no mention of the status of such plans (EC 2010b, a).

### 2.2 Assessments

In the detailed grid assessment, we assess the environmental impacts caused by the GDv05 grid. Electricity grid is here taken to encompass power cables and ancilliary electrical equipment and structures but not offshore wind turbines connected to the transmission network.[2] The grid components studied are array cables, export cables, offshore substation foundations, and electrical equipment for offshore and onshore substations. Besides manufactured grid components, our system of analysis comprises land- and sea-based activities for transport, installation, operations, and maintenance.

LCAs typically measure impact potentials in relation to a reference unit, the "functional unit" in standardized LCA terminology (ISO 2006). Unlike for power generation, for which the use of one unit of electricity delivered as a functional unit is a common feature of LCA literature, the choice of a functional unit for electricity T&D is not trivial. Bumby et al. (2010), studying aerial and underground power distribution, uses 1 mile of an electrical circuit operating for 1 year as the functional unit; Jorge et al. (2012a, b) define 1 km of power line, one transformer unit, etc. operating for one lifetime as functional units in assessments of individual grid components; Harrison et al. (2010) and Jorge and Hertwich (2013) select 1 kWh supplied as a functional unit in assessments of entire transmission grids. The functional unit chosen here is 1 kWh of electricity transmitted in the grid, including both electricity produced in wind farms (61 % of total electricity transmitted over a lifetime) and gross electricity traded from region to region (39 %). In effect, this functional unit reflects cable utilization.

Next, in the comparative assessment of scenarios, we enlarge our view to consider both the North Sea power transmission and power generation in the North Sea and adjoining countries (Norway, Denmark, Germany, Netherlands, Belgium, and Great Britain). The aim is to provide preliminary insights into the comparative environmental merits of two qualitatively different development pathways, examining a considerable number of impact categories. The scenarios compared are GDv05 and ITD20, as described in the previous subsection. The functional unit in the comparative scenario assessment is meeting the demand for electricity in the six North Sea-neighboring countries. In other words, we scale inventories to match absolute requirements for the North Sea grid and northwest Europe power generation.

## 3 Methods, data, and assumptions

Life cycle assessment may be described as a systematic assessment of activities associated with one good or service, of resource use and discharges to the environment that occur as a result of these activities, and potential impacts. In this paper, we study the environmental implications of large-scale deployments of an offshore transmission network and wind energy in the North Sea. We only model impacts that may

[1] Table 1 is an aggregate representation of Windspeed results (Huertas-Hernando et al. 2011).

[2] Wind turbines have been studied extensively before (Arvesen and Hertwich 2012).

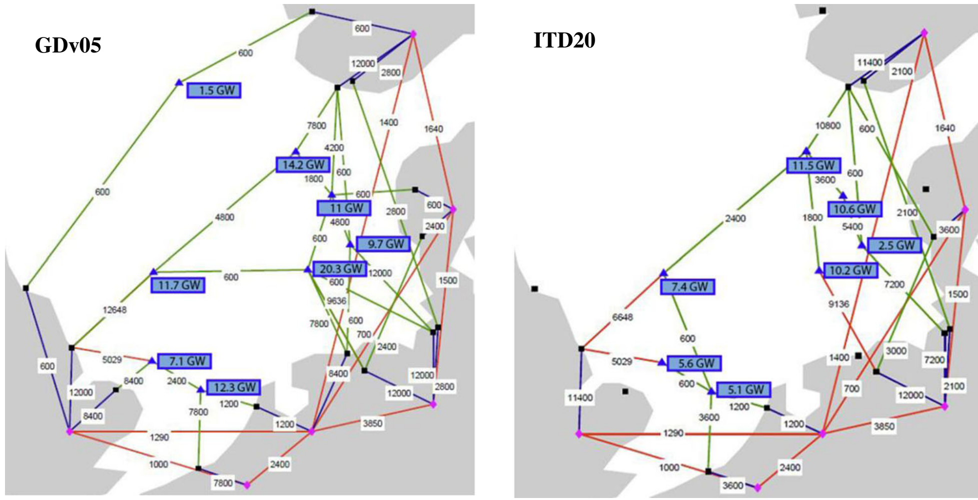


**Fig. 1** Schematic representations of the North Sea grids in GDv05 and ITD20 for the year 2030. *Red lines* represent existing transmission capabilities; *blue* (onshore) and *green* (offshore) *lines* are new or upgraded links. Transmission capabilities for each line are shown in units of megawatt. Nominal outputs of offshore wind park clusters are given in *blue rectangles* (clusters comprise multiple wind parks). Source: adapted from Huertas-Hernando et al. (2011)

arise due to the act of building, operating, and dismantling the grid; we do not attempt to apportion the impacts due to power losses to the transmission system as is done in some other work (Jorge and Hertwich 2013; Harrison et al. 2010). The lifetime of the grid (and all of its individual components) is assumed to be 30 years (Huertas-Hernando et al. 2011). The total amount of electricity transmitted in the GDv05 grid over a 30-year lifetime is 1.46E+13 kWh. We do not consider impacts or benefits that may arise from waste treatment or recycling of components.

## 3.1 Hybrid LCA

A hybrid LCA model combines process-based inventories that are constructed bottom–up and input–output (IO) inventories resulting from top–down representations of economies. The model used in this study incorporates inventories from the Ecoinvent process-LCA database (Ecoinvent 2010) and the EXIOBASE environmentally extended IO database (Tukker et al. 2013). The IO dataset employed has two regions (Europe, rest of the world) and covers 25 types of air emissions, including greenhouse gases (GHGs), non-GHG gaseous compounds, particulate matter, heavy metals, and persistent organic pollutants. ReCiPe characterization factors (Hegger and Hischier 2010) are applied.

We employ a tiered hybrid LCA methodology following Strømman et al. (2006), adding IO-based inventories to processes that are initially defined in a bottom–up fashion. In principle, important operations are modeled bottom–up and in physical terms, while monetary inventories cover numerous operations that would otherwise be neglected. All first-order inputs from the IO system come from the Europe region, but

**Table 1** Annual electricity production (terawatt hour per year) in year 2030 by energy source and countries or regions for GDv05 and ITD20 scenarios

| | Norway and Denmark | | Germany | | The Netherlands and Belgium | | Great Britain | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | GDv05 | ITD20 | GDv05 | ITD20 | GDv05 | ITD20 | GDv05 | ITD20 | GDv05 | ITD20 |
| OW, NSg | | | | | | | | | 300 | 177 |
| OW, other | 35.0 | 33.6 | 90.5 | 53.5 | 43.5 | 34.0 | 68.5 | 76.1 | 238 | 197 |
| Hydro | 153 | 153 | 22.2 | 22.2 | 0.9 | 0.9 | 6.5 | 6.5 | 182 | 182 |
| Onsh. wind | 33.7 | 33.0 | 79.5 | 78.8 | 16.5 | 16.3 | 63.1 | 62.3 | 193 | 190 |
| Solar PV | 0.3 | 0.3 | 57.9 | 59.5 | 10.1 | 9.9 | 11.7 | 11.5 | 80.0 | 81.3 |
| Other ren. | 14.0 | 10.3 | 62.6 | 62.7 | 36.1 | 36.2 | 48.2 | 48.2 | 160 | 158 |
| Hard coal | 0 | 8.1 | 99.1 | 120 | 35.1 | 57.2 | 36.7 | 60.3 | 171 | 245 |
| Lignite | 0 | 0 | 49.6 | 60.0 | 0 | 0 | 0 | 0 | 49.6 | 60.0 |
| Gas, oil | 7.3 | 11.9 | 37.7 | 85.2 | 84.3 | 63.2 | 79.0 | 88.6 | 208 | 249 |
| Nuclear | 0 | 0 | 0 | 0 | 0 | 4.7 | 0 | 45.5 | 0 | 50.1 |

Source: aggregate representation of results in Huertas-Hernando et al. (2011)

*OW, NSg* offshore wind, North Sea grid-connected (wind farms are connected to the grids depicted in Fig. 1 and not allocated to specific countries), *OW, other* offshore wind in unspecified areas, not connected to the North Sea grids and thus not depicted in Fig. 1, *Onsh. wind* onshore wind, *Other ren.* other renewables (mostly biomass)

activity is instigated in rest of the world as well because of interregional trade. We use the same procedure to establish inputs from the IO system as in previous work (Arvesen et al. 2013; Arvesen and Hertwich 2011), utilizing cost information about components and activities to scale IO inputs and then zeroing individual IO entries that include flows already covered in the process-based inventory.

## 3.2 Life cycle inventory for the North Sea grid

Table 2 provides a summary of physical and monetary inputs in our LCA model; further explanations are given in subsections 3.2.1–3.2.3. For reasons of data availability, our physical inventory data for export cables and substation equipment are adapted to 450 kV, not 150 kV as in Windspeed. We obtain monetary cost data for components and their offshore installation from Windspeed documentation (Jacquemin et al. 2011) and operational costs from Arvesen et al. (2013). Future cost reductions for components are included on the basis that learning benefits accrue before the grid is completed; the average reduction across all components and time span is 38 % compared with current levels.[3] Where appropriate, we adjust cost numbers using average inflation rates to match the year 2000 transactions data in EXIOBASE.

### *3.2.1 Array cables*

Consistent with Windspeed, we assume three-core copper conductor cables of two different sizes are utilized to transfer electricity from wind turbines rated at 5 MW each. The wind turbines are arranged in a 15×8 grid (wind farm capacity 15×8×5 MW=600 MW)[4] (Jacquemin et al. 2011). Assuming a power density of 2 MW/km$^2$ and following relationships outlined in Jacquemin et al. (2011), we find that 83 km of 3×240-mm$^2$ and 94-km 3×630-mm$^2$ Cu cables (AC, 33 kV) are needed per wind farm. This means that 12,100 km (7,320 km) of 3×240 mm$^2$ and 13,700 km (8,290 km) of 3×630 mm$^2$ are needed in GDv05 (IDT20) in total. We use the approach of Birkeland (2011) to estimate the weights of individual cable layers from layer thickness values (ABB 2010; Nexans 2011) and scale to actual total weight.[5] Zinc coating of steel armoring is included. We use numbers for direct energy use in manufacturing derived in Arvesen and Hertwich (2011) from an industry report (ABB 2008). Finally, we obtain marine vessel fuel oil consumption values for tie in of cables, cable laying with plough, inspection during operation and end-of-life removal from Arvesen et al. (2013), and scale to take into account greater travel distances.

### *3.2.2 Export cable*

The export cables modeled in this study are based on the deep-water part of the existing NorNed high voltage, direct current (HVDC) link, a flat cable rated at 450 kV and consisting of 2×790-mm$^2$ copper (Cu) conductors, mass-impregnated paper insulation, and steel and lead sheeting (Birkeland 2011; ABB 2013). In a similar manner as for the array cables, we establish the material composition of the export cable (Birkeland 2011) and take into consideration manufacturing (ABB 2008; Arvesen and Hertwich 2011) and cable laying, inspection, and removal (Arvesen et al. 2013). A total of 39,800-km (28,600 km) HVDC cabling is needed in GDv05 (ITD20).

### *3.2.3 Substation*

Two functions of the offshore and onshore substations are to convert from AC to direct current (DC) and vice versa and to transform voltage. There are 147 (89) sea-based and 154 (95) land-based substations in GDv05 (ITD20). Windspeed assumes high-capacity voltage source converters (VSCs), a technology that has not yet entered commercial use (Huertas-Hernando et al. 2011; Callavik et al. 2012). As physical descriptions of VSC, AC/DC converters are not available, our physical inventory (representing material and energy inputs to manufacturing) is from information on an AC/AC transformer (ABB 2012a). Switchgear and breakers are integral parts of this inventory. For offshore substations, we assume a steel six-legged jacket foundation concept and 40-m water depth on average, based on water depth data from 4C Offshore (2013). At this water depth, the jacket mass is expected to be 3,000 t (Jacquemin et al. 2011). The topside, excluding electrical equipment, weighs 1,170 t (Jacquemin et al. 2011) and is modeled as made of steel. Sea-based operations are modeled based on fuel oil consumption figures in Arvesen et al. (2013) and include the use of construction ships for installation and service boat for inspection and maintenance.

## 3.3 Comparative scenario assessment

We apply hybrid life cycle inventory modeling for the GDv05 and ITD20 North Sea power systems, respectively, using inventory data compiled for this study to model transmission and data from previous work (Arvesen et al. 2013) to model additional inputs needed for wind power. Electric power generation from other sources is represented by appropriate Ecoinvent processes (Ecoinvent 2010). By mapping all of

[3] See Cameron et al. (2011) for details on how learning is modeled in Windspeed.

[4] While 600 MW wind farm capacity is assumed here for the purpose of determining typical array-cabling requirements, the wind farm cluster capacities in Fig. 1 are not divisible into 600 MW units.

[5] Scaling is performed because the sum of estimated cable layer weights does not exactly match the known, total weight. Without the scaling, estimated totals amount to 80–90 % of real totals.

**Table 2** Physical and monetary inventories for main grid components and operations and maintenance (O&M)

| | | Array cables (per 600 MW wind farm) | Export cables (per kilometer) | Substation structure (per unit) [a] | Substation equipment (per unit) | O&M (per entire GDv05 grid) |
|---|---|---|---|---|---|---|
| Material and energy inputs to manufacturing [b] | | | | | | |
| Copper | Tonne | 1.89E+03 | 1.41E+01 | | 3.61E+02 | |
| Steel, low alloy | Tonne | 2.01E+03 | 3.52E+01 | 4.17E+03 | 1.44E+03 | |
| Zinc coating of steel | Square meter | 7.12E+04 | 5.65E+02 | | | |
| Lead | Tonne | 1.28E+03 | 2.49E+01 | | | |
| Polyethylene, HDPE (insulation) | Tonne | 3.45E+02 | | | | |
| Polypropylene | Tonne | 2.12E+02 | 3.25E+00 | | | |
| Kraft paper (insulation) | Tonne | | 5.96E+00 | | 5.87E+01 | |
| Other materials, substation [c] | Tonne | | | | 5.90E+02 | |
| Electricity | Kilowatt hour | 4.45E+06 | 9.37E+04 | | 6.78E+06 | |
| Natural gas | Megajoule | 4.45E+06 | 6.43E+04 | | 2.71E+06 | |
| Onshore and offshore transport requirements [d] | | | | | | |
| Lorry, >32 t capacity | Tonne-kilometer | 1.16E+06 | 2.38E+05 | 4.20E+05 | 5.26E+05 | |
| Marine vessels, MGO fuel | Megajoule | 8.36E+04 | | 9.08E+03 | 1.66E+04 [a] | 1.20E+06 |
| Marine vessels, HFO fuel | Megajoule | | 7.79E+04 | 1.37E+04 | | |
| Monetary inputs from IO sectors [e] | | | | | | |
| Manuf. cement, lime and plaster | M€ | | | 3.57E+00 | | |
| Manuf. fabricated metal products | M€ | | | 1.79E+00 | 2.96E+00 | |
| Manuf. el. machinery and app. | M€ | 2.78E+01 | 1.63E−01 | | 2.52E+01 | 7.79E+02 |
| Construction | M€ | 7.96E+00 | 1.16E−01 | 7.15E+00 | 1.48E+00 | 1.95E+03 |
| Sea and coastal water transport | M€ | 3.98E+00 | 9.30E−02 | 3.57E+00 | | 3.89E+02 |
| Research and development | M€ | | 4.65E−02 | | 2.05E+01 | |
| Other business activities | M€ | | 4.65E−02 | 1.79E+00 | 2.05E+01 | 7.79E+02 |

*MGO* marine gas oil, *HFO* heavy fuel oil, *Manuf.* Manufacturing of, *El.* electrical, *App.* apparatus

[a] Applies to offshore substations only. Includes substructure (foundation) and topside structure

[b] Based on Birkeland (2011), Arvesen et al. (2013), ABB (2010, 2012a), Nexans (2011), and Jacquemin et al. (2011)

[c] Comprises lubricating oil (78 %), wood packaging (19 %), paint (2.7 %), and resin (0.2 %)

[d] Onshore: assuming 100 km from facility to port (installation phase; all components); 100 km from port to treatment (end-of-life; cables only). Offshore: adapted from Arvesen et al. (2013)

[e] Total costs: adapted from Jacquemin et al. (2011); sectoral breakdowns: own assumptions. Unit: million Euros (M€), year 2000 prices

these data to the GDv05 and ITD20 electricity mixes (Table 1), we are able to study—in a life cycle view—both the North Sea power transmission and northwest Europe power generation under GDv05 and ITD20 scenarios.

## 4 Results and discussion

### 4.1 Detailed grid assessment

An overview on impact indicator results, per functional unit and componentwise, is provided in Table 3. The total GHG emission intensity of the GDv05 grid is 2.49 g $CO_2$-Eq per kWh. Further, Fig. 2 shows indicator results for ten categories broken down to main components and environmental stressor sources. The nine stressor sources comprise seven categories of processes in the physical subsystem: "Electricity" represents direct (in-plant) stressors incurred in power generation; "heat" covers incineration and other processes whereby heat is delivered; "waste management and treatment" encompasses all types of treatment, incineration, and deposition of waste; "transportation" takes place onshore or offshore and includes all marine vessel operations; etc. The two IO categories together represent all stressors elicited in the IO subsystem.

As is evident from Fig. 2, export cable is the largest contributor for all impact categories, causing nearly half of total climate change effects and roughly 60 % of totals for other impact types (e.g., toxic effects in humans and ecosystems). When measured per km of cable length, the carbon footprint of the export cable (HVDC, 450 kV, 2×790-mm$^2$ Cu) is 215 t $CO_2$-Eq/km, of which 117 t $CO_2$-Eq/km is generated in the physical subsystem. This compares with a

**Table 3** Total indicator values per functional unit (GDv05 grid) and per grid component by 15 impact categories

| | | Total, GDv05 grid (per kilowatt hour) | Array cables (per 600 MW wind farm) | Export cable (per kilometer) | Offshore substations (per unit) | Onshore substations (per unit) | O&M (per GDv05 grid) |
|---|---|---|---|---|---|---|---|
| Climate change | kilogram $CO_2$-Eq | 2.49E−03 | 3.38E+07 | 4.31E+05 | 4.44E+07 | 2.61E+07 | 3.72E+09 |
| Fossil depletion | kilogram oil-Eq | 4.17E−04 | 5.94E+06 | 7.92E+04 | 6.30E+06 | 3.17E+06 | 6.65E+08 |
| Freshw. ecotox. | kilogram 1,4-DCB-Eq | 8.63E−05 | 2.24E+06 | 1.88E+04 | 7.20E+05 | 5.11E+05 | 1.66E+06 |
| Freshw. eutroph. | kilogram P-Eq | 3.95E−06 | 1.06E+05 | 8.63E+02 | 2.83E+04 | 2.36E+04 | 5.05E+04 |
| Human toxicity | kilogram 1,4-DCB-Eq | 8.14E−03 | 2.23E+08 | 1.80E+06 | 5.19E+07 | 4.54E+07 | 1.53E+08 |
| Marine ecotox. | kilogram 1,4-DCB-Eq | 3.10E−04 | 2.61E+06 | 2.16E+04 | 8.07E+05 | 5.85E+05 | 3.71E+07 |
| Marine eutroph. | kilogram N-Eq | 9.96E−05 | 4.95E+04 | 4.54E+02 | 2.96E+04 | 1.75E+04 | 5.35E+06 |
| Metal depletion | kilogram Fe-Eq | 2.50E−06 | 6.69E+07 | 5.63E+05 | 2.63E+07 | 1.54E+07 | 4.19E+06 |
| Land use | square meter-years | 2.18E−04 | 7.25E+05 | 6.41E+04 | 1.88E+06 | 1.62E+06 | 6.64E+06 |
| Ozone depletion | kilogram CFC-11-Eq | 1.02E−10 | 1.27E+00 | 1.90E−02 | 1.34E+00 | 7.38E−01 | 9.62E+05 |
| Particulate matt. | kilogram PM10-Eq | 8.34E−06 | 1.55E+05 | 1.49E+03 | 1.14E+05 | 6.28E+04 | 2.41E+02 |
| Phot. oxidant | kilogram NMVOC | 1.32E−05 | 2.17E+05 | 1.98E+03 | 1.95E+05 | 1.05E+05 | 1.34E+07 |
| Terr. acidification | kilogram $SO_2$-Eq | 2.14E−05 | 4.02E+05 | 3.85E+03 | 2.59E+05 | 1.59E+05 | 3.71E+07 |
| Terr. ecotoxicity | kilogram 1,4-DCB-Eq | 5.15E−07 | 1.18E+04 | 1.10E+02 | 4.76E+03 | 3.32E+03 | 3.90E+07 |
| Water depletion | cubic meter | 2.04E−05 | 1.38E+05 | 1.55E+03 | 7.49E+04 | 5.32E+04 | 2.07E+05 |

*Freshw.* freshwater, *Ecotox.* ecotoxicity, *Eutroph.* eutrophication, *Particulate matt.* particulate matter formation, *Phot. oxidant* photochemical oxidant formation, *Terr* terrestrial

GDv05

ITD20

total GHG emission intensity of 125 t $CO_2$-Eq/km calculated using process-LCA in Jorge et al. (2012a) for an oil-filled submarine cable (HVDC, 150 kV, 2×800-mm$^2$ Cu). Impact potentials caused by array cables are a half to a third of export cable indicator values in our results (Fig. 2). In reality, the amount of array cabling needed and cable design vary depending on the spacing between wind turbines, water depth, and seabed topography. If we change the array cabling requirement by 20 %, the total GHG emission intensity changes by 2.7 %.

Operations and maintenance represent 19 % of total indicator values at the most (photochemical oxidant formation) and 10–12 % for several impact categories, largely because of emissions by vessels. In total, direct emissions from transportation represent 13 % of total GHG and appear as relatively more important for acidification (16 % of total, mainly due to $SO_2$ and $NO_x$ from sea vessels), marine eutrophication (19 %, $NO_x$), and photochemical oxidants (30 %, $NO_x$ and NMVOC). Selective catalytic reduction of $NO_x$ on marine vessels can potentially reduce acidifying and eutrophying effects and formation of photochemical oxidants appreciably (Bengtsson et al. 2011; Arvesen et al. 2013). Nearly one third (31 %) of the GHG emissions in the physical subsystem come from fossil fuel burning in power stations, illustrating a general need to use fossil electricity of today to develop electricity infrastructures for tomorrow (Arvesen 2013). It can be noted that replacement of parts is not considered by Windspeed and not included here either. If we instead assume that 5 or 10 % of all cables and electrical equipment needs to be replaced once during the lifetime, total GHG emissions would increase by 4 or 8 %.

Mining of copper and iron constitutes 40 and 21 % of metal depletion burden, respectively. In the academic literature, concerns about future availability of copper are raised based on scenarios with worldwide economic development (Gordon et al. 2006) or electricity transmission expansion (Kleijn and van der Voet 2010).[6] The bulk of contemporary criticality assessments do not consider copper as critical, however (Erdmann and Graedel 2011). There is no agreed upon method to measure abiotic resource depletion in LCA; competing methods approach the problem differently and may give different results (Steen 2006; Hauschild et al. 2013).

Toxic effects in humans and aquatic ecosystems and freshwater eutrophication are almost entirely or largely caused by leakages from disposed copper and iron mine tailings and overburden material. It should be noted that indicator scores for toxicity are very uncertain owing to difficulties in enumerating and characterizing large numbers of substances with often complex effect chains in the environment (Rosenbaum et al. 2008; Pettersen and Hertwich 2008; Hauschild et al. 2013). Also, declining ore grades for copper—an important ingredient of offshore grids—can be expected to exacerbate

[6] Tilton and Lagos (2007) present a contrasting view.

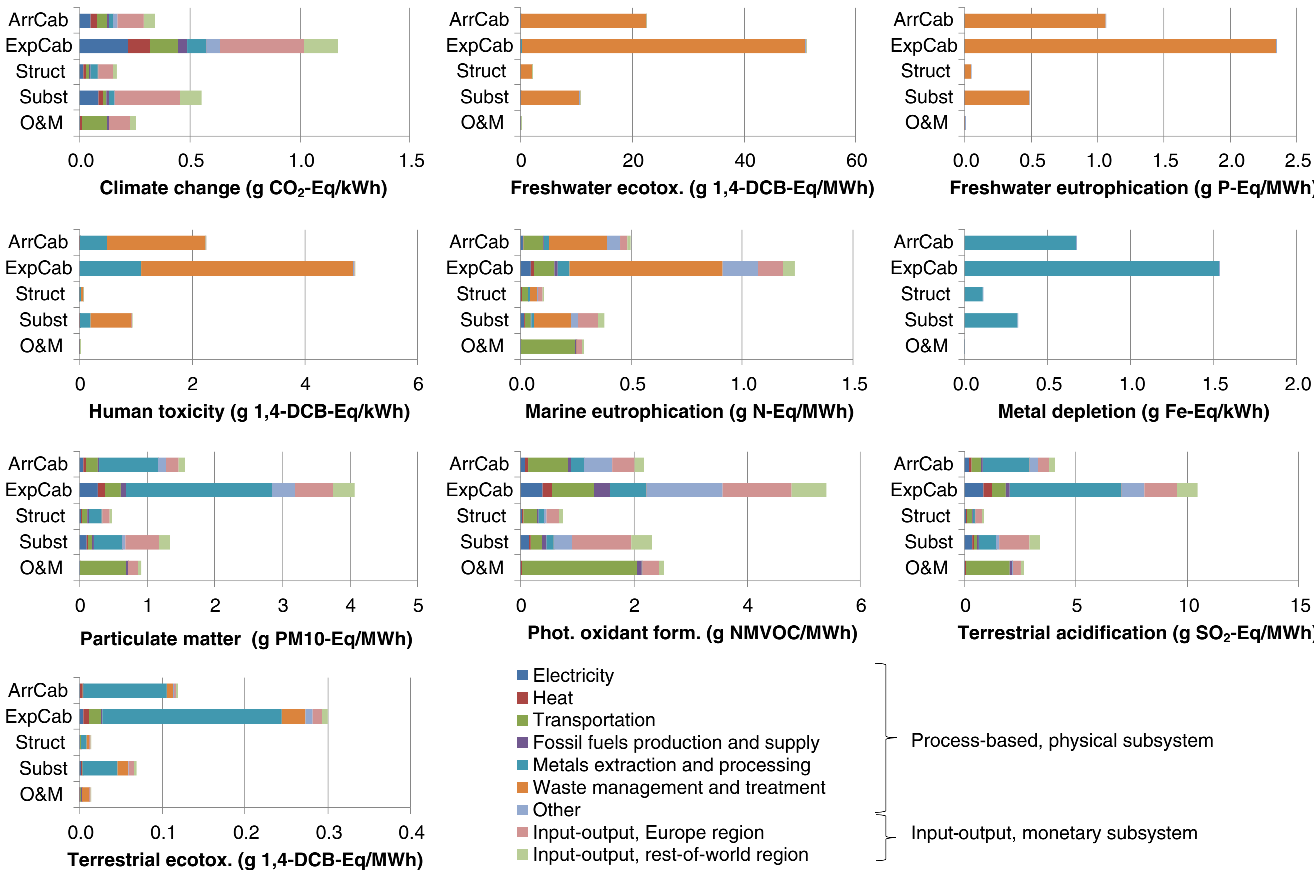


**Fig. 2** Impact indicator results by five components and nine stressor sources per kilowatt hour or megawatt hour transmitted (GDv05). *Ecotox.* ecotoxicity, *Phot. oxidant form.* photochemical oxidant formation. Components: *ArrCab* array cables, *ExpCab* export cable, *Struct* substructure and topside for substation offshore, *Subst* electrical equipment (voltage source converter, transformer, breakers, and switchgear) for substations offshore and onshore, *O&M* operations and maintenance

environmental damage connected with copper mining in the future (Mudd 2010; Prior et al. 2012).

In this work, we assume a uniform system lifetime of 30 years, following Windspeed. Prolonging the system life span to 35 years in our model reduces the total GHG emission intensity by 13 %. For array cables, the 30-year lifetime is in the upper end of the spectrum of similar assumptions in past economic (Blanco 2009) and environmental (Arvesen and Hertwich 2012) assessments of wind power. Some electrical equipment may last longer than 30 years; for example, ABB (2012a, 2012b) assume a 35-year lifetime for transformer stations. Further, it is conceivable that the technical lifetime of the steel substructures of offshore substations may exceed 30 years, perhaps by a substantial margin. At the same time, real lifetimes will depend not only on technical considerations but also economic and other considerations.

Previous research suggests that hybridized inventory modeling gives much more complete coverage of relevant activities than purely process-based techniques (e.g., case studies for renewable energy (Zhai and Williams 2010; Crawford 2009; Wiedmann et al. 2011) or review (Majeau-Bettez et al. 2011)). In our results, the IO subsystem generates 52 % of the total GHG emissions. Of these, 34 % is generated in manufacturing industries, 25 % in the power sector, and 13 % in transport. The coverage of stressor types in our IO data set is much less exhaustive than in the process-LCA data, which can explain the lower relative IO subsystem contributions for other impact categories than climate change. In general, there is large uncertainty involved in defining the interface between the process-based and IO subsystems in tiered hybrid LCA. Future research into tiered hybrid LCA method development may address this weakness by systemically comparing counterpart activities in the process-based and IO subsystems so as to assess how the subsystems are best combined. Also, current hybrid models offer limited support for tracking material flows through IO supply chains.

The individual contributions of components to IO subsystem emissions are evident from Fig. 2. The relatively high costs for substation equipment (Table 2) translate into sometimes sizeable IO subsystem contributions for this component ("Subst" in Fig. 2). These high costs and consequent high IO contributions reflect the current research and development (R&D) phase of VSC AC/DC converter technology and are highly uncertain (Huertas-Hernando et al. 2011). Looking at

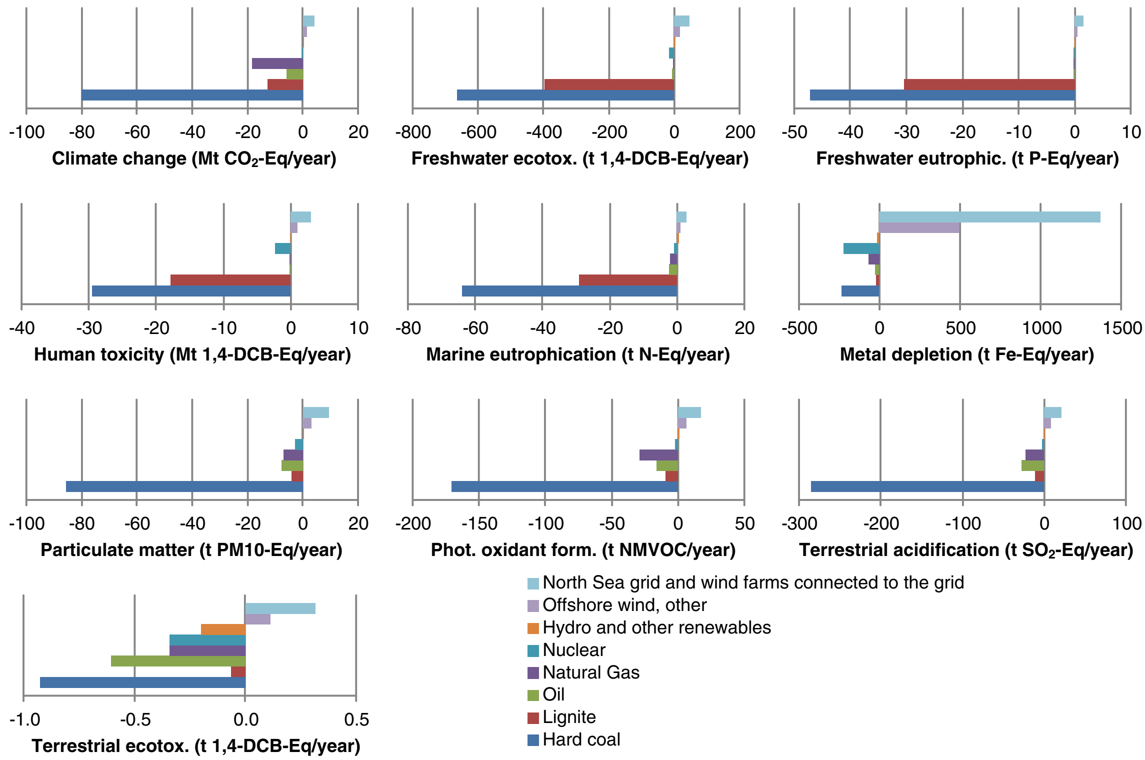


**Fig. 3** Net potential environmental burdens (*positive axis*) or benefits (*negative axis*) of GDv05 relative to ITD20. The length of the bars represent, for eight power transmission or generation technologies individually, the total indicator results for GDv05 *less* the corresponding results for ITD20, measured on an average annual basis for an assumed lifetime of 30 years. *Ecotox.* ecotoxicity, *Eutropic.* eutrophication, *Phot. oxidant form.* photochemical oxidant formation

the GHG emissions embodied in R&D activity in our IO submodel, 43 % of the emissions occur directly in the R&D sector and 17 % in the power sector.

Another element that may contribute to climate impact for substations is leakage of sulfur hexafluoride ($SF_6$, an extremely powerful GHG) from $SF_6$ gas-insulated switchgears (Jorge et al. 2012b). Our analysis does not include $SF_6$ losses, as the data source used for substation equipment assumes air-insulated and not $SF_6$-insulated switchgear technology. If we had instead used a different source describing a 420-kV $SF_6$-insulated switchgear (ABB 2012b), total losses of $SF_6$ during manufacturing, operation, and disposal would amount to 0.11 g $CO_2$-Eq. per kWh.

## 4.2 Comparative scenario assessment

Figure 3 compares the estimated total life cycle impact potentials of the North Sea power generation and transmission and other power generation in the North-Sea-neighboring countries for GDv05 and ITD20 scenarios. Results are depicted as average annual GDv05 impact potentials *less* average annual ITD20 potentials over the 30-year time frame. Thus, a bar on the positive (negative) axis represents an environmental burden (gain) in moving from ITD20 to the more ambitious GDv05 scenario. The North Sea power systems are more resource demanding in GDv05 than ITD20, and hence, the top, “North Sea grid” bar always represents a value on the positive axis. Conversely, the lower contributions from coal-fired power stations in GDv05 than ITD20 entail environmental benefits by all indicators.

According to the results, the act of building, operating, and dismantling the North Sea wind power and transmission systems causes 310 million tonnes (Mt) (GDv05) or 190 Mt (ITD20) $CO_2$-Eq emitted. Of this, 13–14 % is due to grid constituents, the remainder to other activities related to wind farms. These emissions are modest when compared with the life cycle emission benefits of displacing fossil-fuel-based electricity: In total, across all technologies (horizontal bars in Fig. 3), the net climate change mitigation achieved in deploying GDv05 instead of ITD20 is 112 Mt $CO_2$-Eq per year, and the net acidic pollution abatement 320 t $SO_2$-Eq per year. Figure 3 similarly shows clear net reductions in potential environmental effects for all impact types except metal depletion, shedding light on how polluting conventional fossil power is across an array of impact categories. Among the fossil fuels, phase out of hard coal and (to a lesser degree) lignite most consistently leads to significant reductions in potential environmental damage. Besides the grid components, wind turbines and foundations give rise to metal depletion owing to copper, iron, and steel-alloying element extraction (Arvesen et al. 2013).

The elements of uncertainty discussed above for the detailed grid assessment are relevant to consider here as well. Additionally, three cautionary flags about the comparative scenario assessment are raised here, as follows. First, investments in onshore grids are needed to accommodate increasing shares of intermittent supply. Studying such grid reinforcements, meanwhile, was not part of the scope of Windspeed (Huertas-Hernando et al. 2011) and is disregarded here as well. Second, it is worthwhile to bear in mind that both GDv05 and IDT20 assume substantial transnational coordination of offshore wind and grid development.[7] With less coordination, a meshed offshore grid is unlikely to emerge and different results may be obtained. Third, by taking future electricity mixes as given, we implicitly assume that real barriers—technological, social, or political in nature (Arvesen et al. 2011; Moe 2010; Unruh 2000; York 2012)—will be overcome. Nevertheless, the scenario assessment indicates that the large-scale deployment of the North Sea wind power and power transmission and phase out of fossil electricity will give environmental benefits by an array of criteria—the one exception being metal depletion.

## 5 Conclusions and outlook

Investments in power grids are substantial and a central element in climate change mitigation. The balancing of supply and demand across larger grid areas allows for the integration of higher shares of variable renewable electricity sources without expensive storage or backup (IEA 2012). Despite this, LCA case studies of (existing or foreseen) systems for electricity T&D are scarce. To our knowledge, the current work is the first LCA of a larger offshore grid. It fills a gap in the literature by investigating the environmental effects of a proposed HVDC transmission network in the North Sea, considering a range of impact categories. Besides giving impact potentials per unit of electricity transmitted, the results illuminate differences among impact categories with respect to which components lead to environmental pressures and identifies the activities where the pressures occur.

The comparative scenario assessment provides tentative insights into the potential environmental benefits of following relatively more ambitious development pathways for the North Sea grid and wind power systems. More research is needed to establish a better understanding of the environmental implications of electricity T&D. This may involve new analyses of components or scaled-up analyses of entire systems. It may also involve the combination of life cycle and optimization perspectives in integrated LCA and energy planning (Riahi et al. 2012; Huertas-Hernando et al. 2011; Fripp 2012) models. Such integrated models could be useful in identifying trade-offs or prospects for co-maximization of different types of environmental and economic benefits.

Finally, we note that decision makers should also adequately consider impacts due to power losses, which are not studied here in order to focus attention on other aspects, and effects of offshore grids on the surrounding marine life.

[7] See Cameron et al. (2011) for details on the scenarios considered in Windspeed.

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